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Computed Unsteady Flows of Airfoils at High Incidence

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The flow over an airfoil at an angle of attack above the static stall angle would ordinarily be massively separated. Under dynamic conditions, the onset of stall can be delayed to an angle, depending on the type of unsteadiness, the freestream Mach number and the transition process, much higher than that for static stall. The stall onset mechanisms under dynamic conditions are unclear. Due to extreme difficulties involved, experimental investigations, so far, have provided insufficient information about the flow field for the identification of the onset mechanisms. A course of classical boundary layer analysis augmented with numerical experiments and measured data is chosen here instead, with the hope that the identification of onset mechanisms can be more systematic and quantitative.

To avoid confusion in terminology, the onset of stall, for the cases studied here, is defined as the conditions at which the peak suction on the airfoil attains the maximum value before the airfoil reaches the maximum angle of attack in a course of upward pitching motions. It is found that the onset of stall is delayed with increased frequency of oscillation as long as the flow remains subsonic. Once the flow is locally supercritical, the onset of stall becomes much less sensitive to increased frequency but has a strong dependency on the freestream Mach number. The dependency of the onset on the Mach number is not affected by the airfoil geometry as much as its dependency on the reduced frequency is. Before the onset of stall, the instantaneous pressure distributions over the airfoil can be considered quasi-steady, and are predictable using inviscid theory.

Two airfoils, the NACA 0012 and the Vr7, which have different dynamic stall characteristics are chosen for our study here. An analysis of the boundary layers on these two airfoils at various conditions suggests that separation bubble bursting, or the failure of reattachment of the separating boundary layer, deserves more investigations and attention as a key onset mechanism than it has been given. This analysis, which is based on computed inviscid flows and classical theories for static stall, suggests that once the flow becomes locally supersonic, the onset of stall is a result of the interaction between the forming shock and the steepening laminar boundary layer. It also gives an explanation to the differences between the onset characteristics of the two airfoils.

The sensitivity of stall onset on transition is studied by computing the flow over an airfoil at conditions near stall and varying the switch-on location of the turbulence model for the Reynolds averaged Navier-Stokes code used for this study. Figure 1a shows a computed lift history of the NACA 0012 airfoil for the a freestream Mach number of 0.301 and at a stationary incidence angle of 11.5 degree. A turbulence model is turned on at 2% chord. The flow is subsonic everywhere throughout the history for this lower angle of attack. Notice that a steady state is reached after roughly 1500 iterations. However, when the turbulence model is turned on at 5% chord, Figure 1b, the lift history fluctuates wildly (solid line) if nonuniform time steps are used, and periodically if a time accurate marching method (dotted line) is used. A leading edge separation bubble is observed in the boundary layer of these flows. The size of the separation bubble is directly related to the turn-on location of the turbulence model, which causes the separating boundary layer to reattach if conditions allow. A move of this location from 2% to 5% changes the stability of the flow. The fluctuations in the latter case are due to unsteady separation and subsequent reattachment of the bubble. A change of incidence angle from 11.5 to 12.5 has a drastic effect on the lift history. With the turbulence model turned on at 2%, not only does the lift not reach a steady value as for the lower incidence case, it fluctuates periodically with large amplitudes, Figure 1c. As the lift reaches a high value, a local supersonic region is form near the leading edge. The separation bubble beneath this region interact strongly with the supersonic flow. A separation vortex is formed when the supersonic region reaches a certain size. The vortex then interacts as it moves with the boundary layer, causing the lift to drop to a value below zero, where another cycle of lift fluctuation begins. For 12.5 degrees, a stable solution can be found if the turbulence model is turned on before 1% chord. For an even higher angle of attack close to the static stall value, at 13.25 degrees, a mere change of transition locations from 1.25 to 1.35%, which differ by one grid point and are before and after the computed shock location respectively, causes the flow from reattachment to massive separation. For a lower freestream Mach number, 0.185, separation is less sensitive to the transition location as the angle of attack is increased.

Figure 1a, M=0.301 Alpha=11.5 T.P.@ 2%

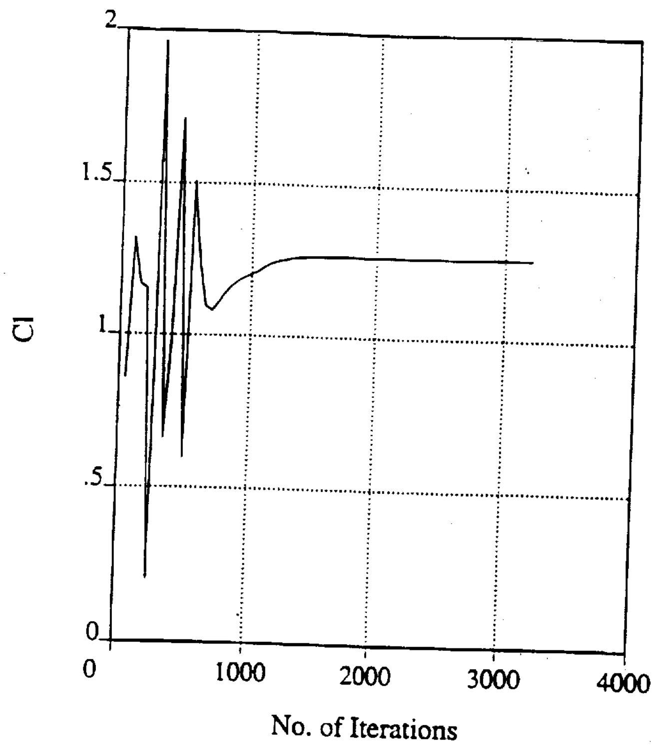


Figure 1b, M=0.301 Alpha=11.5 T.P.@ 5%

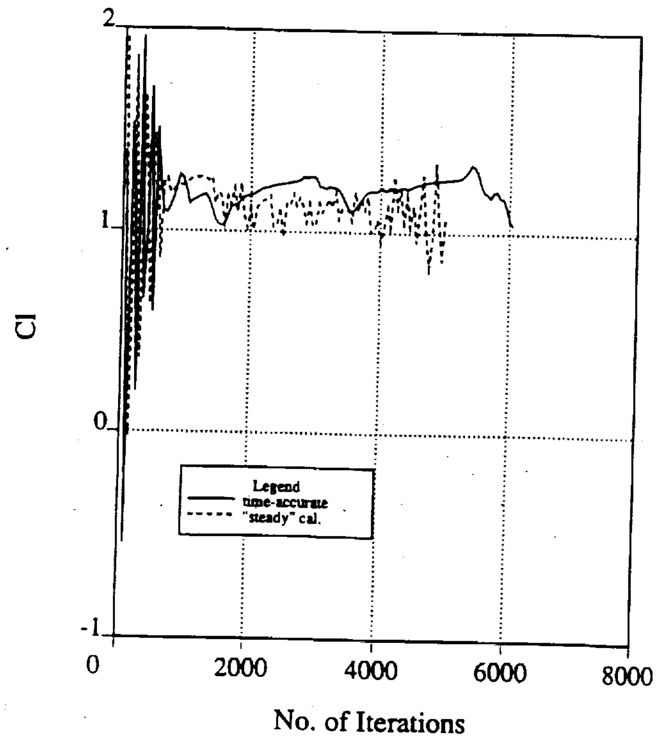


Figure 1c, M=0.301 Alpha=12.5 T.P.@ 2%

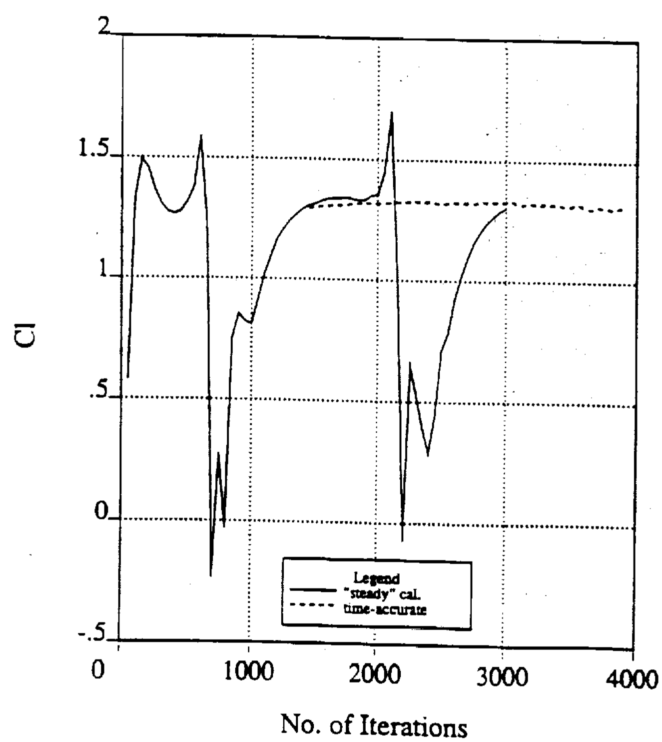
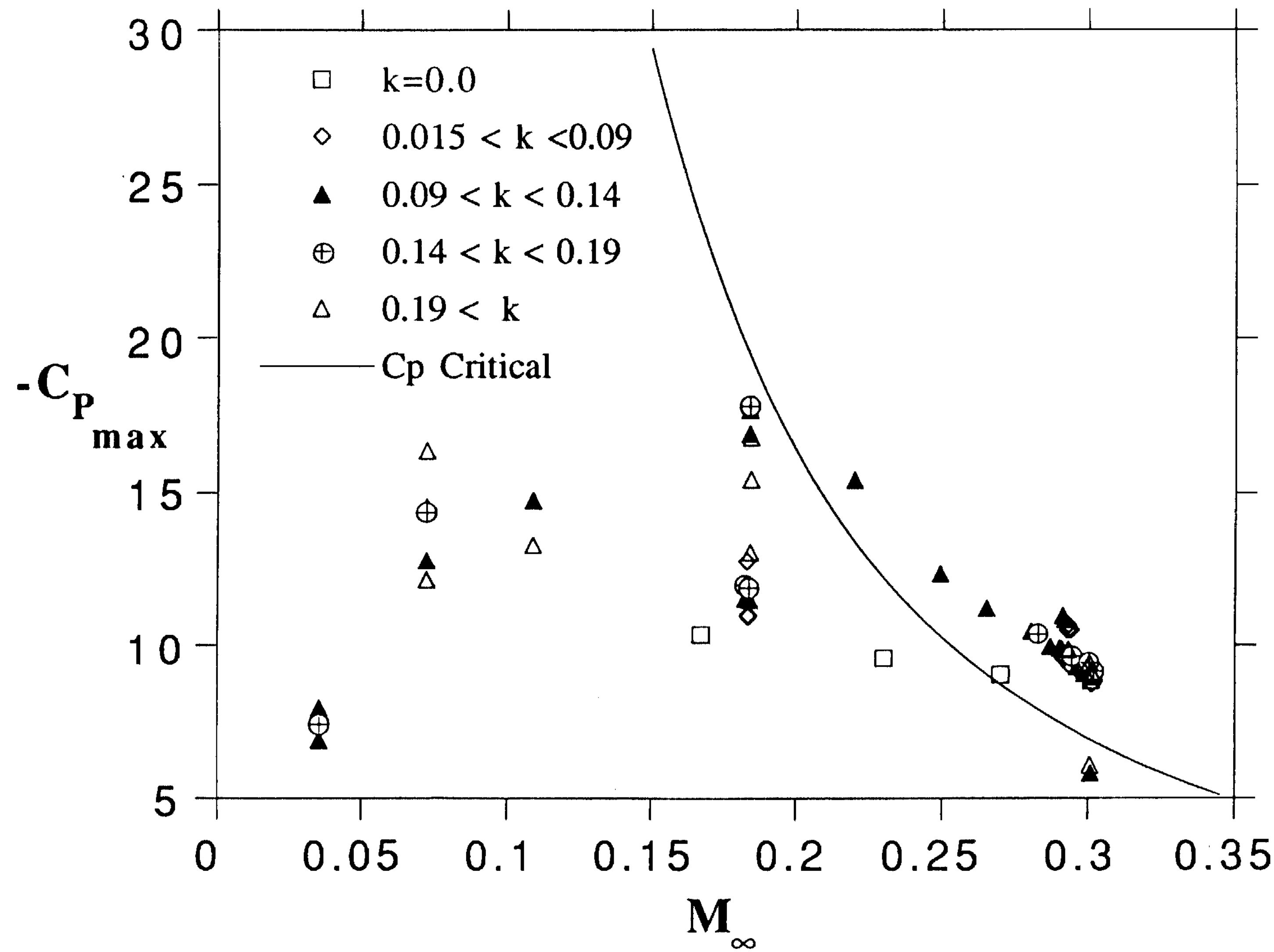
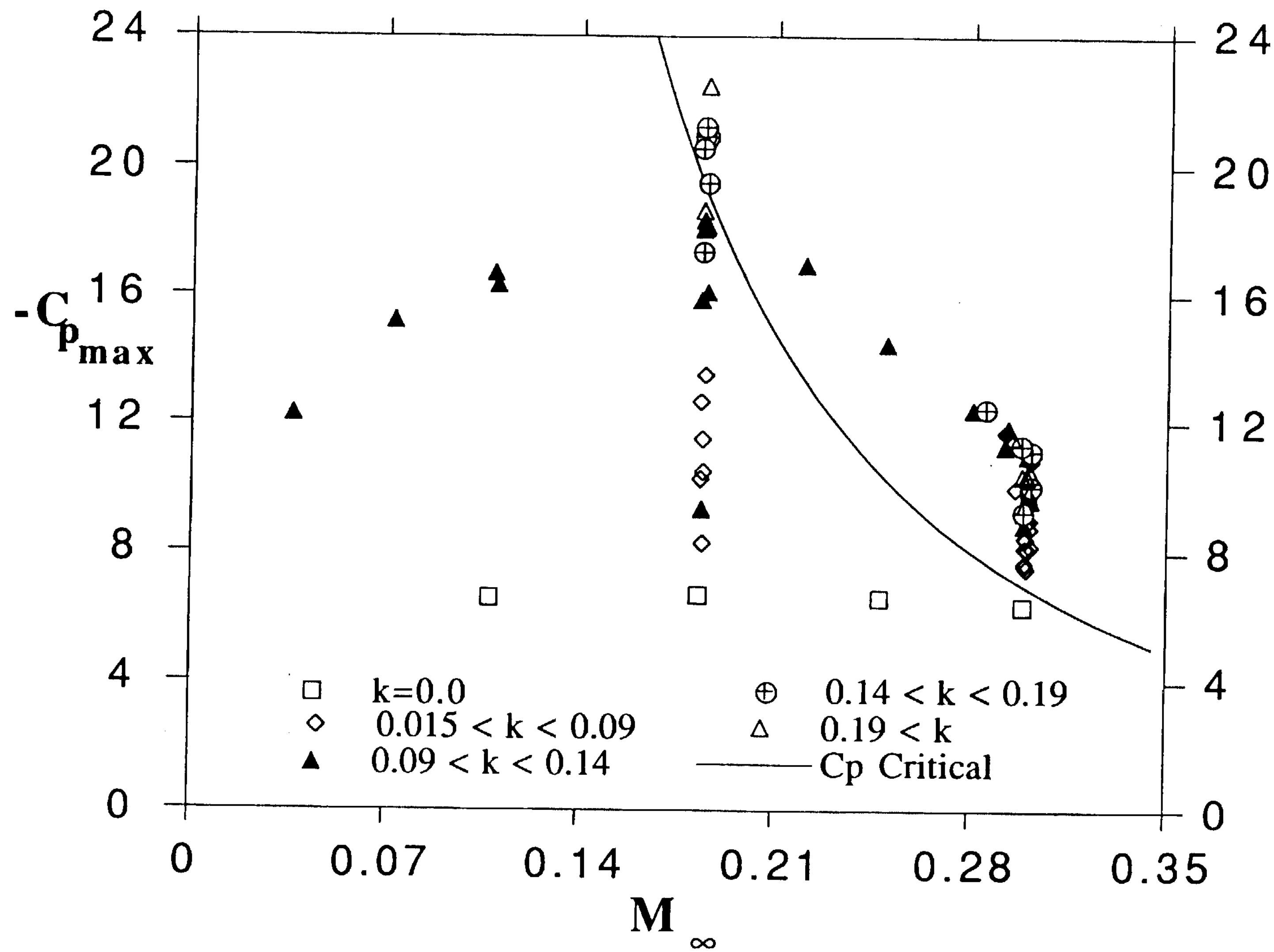


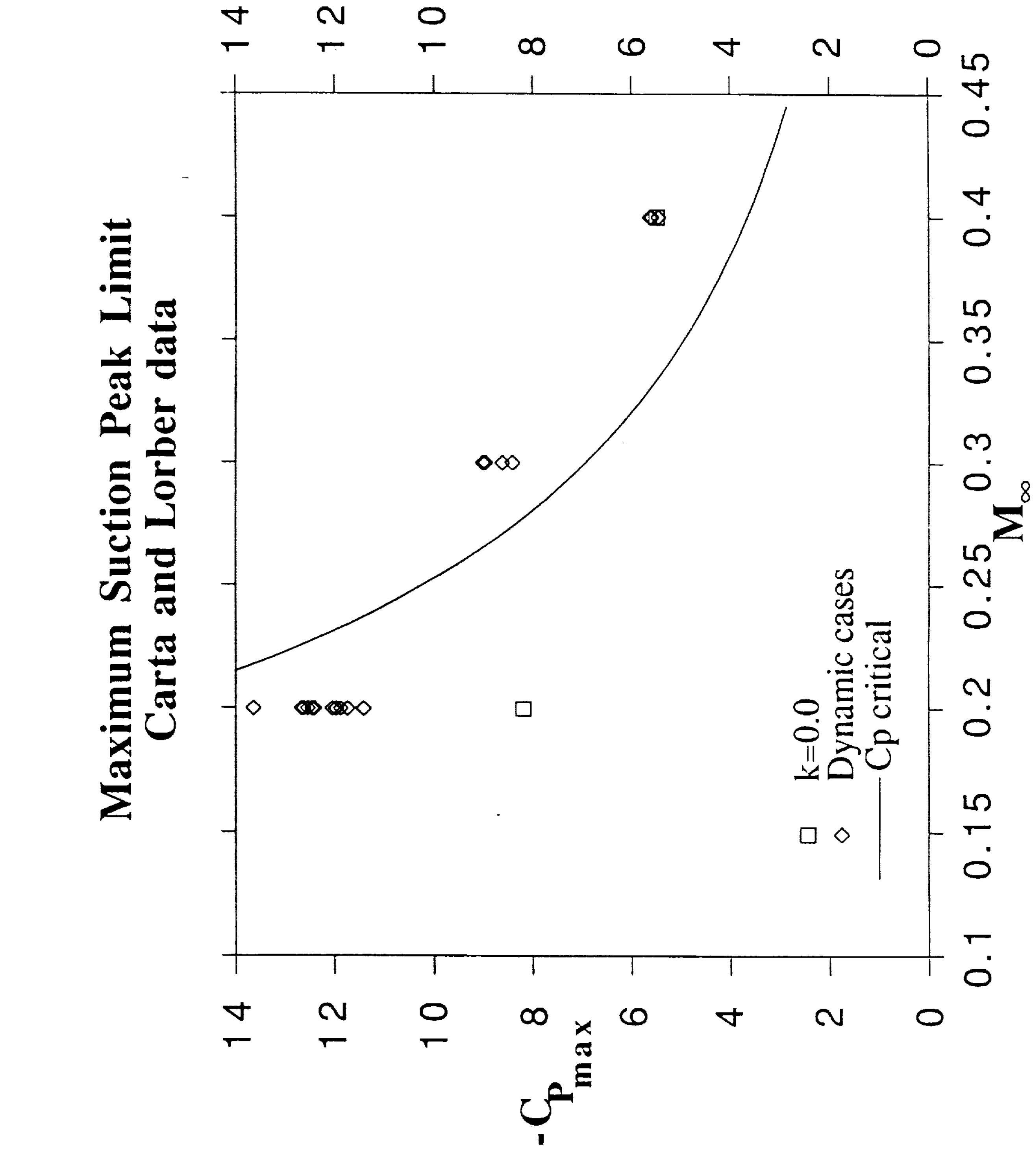
Figure 1, Lift history computed using a Navier-Stoke solver with the turbulence turned on at different locations.

Maximum Suction Peak Limit NACA 0012 Airfoil

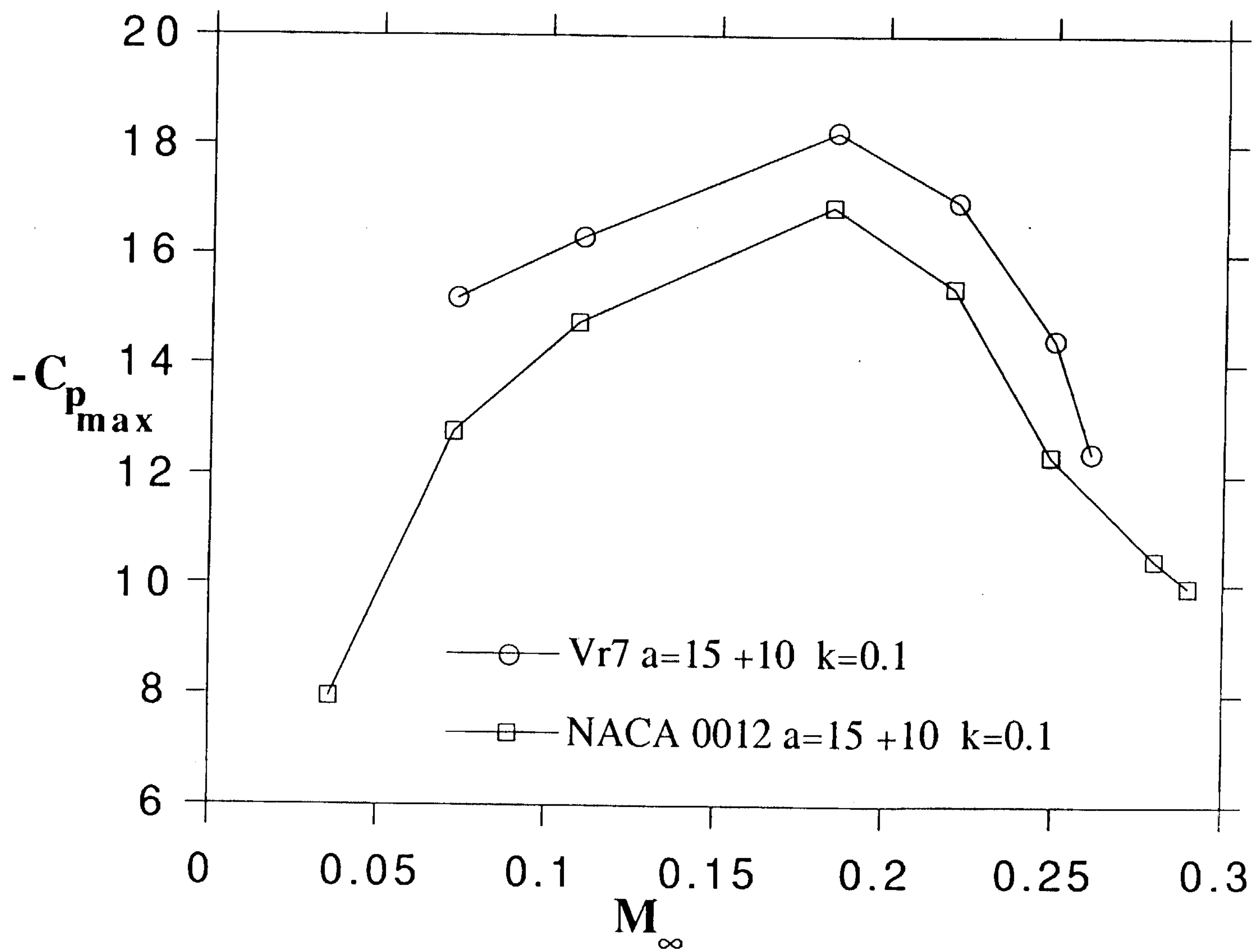


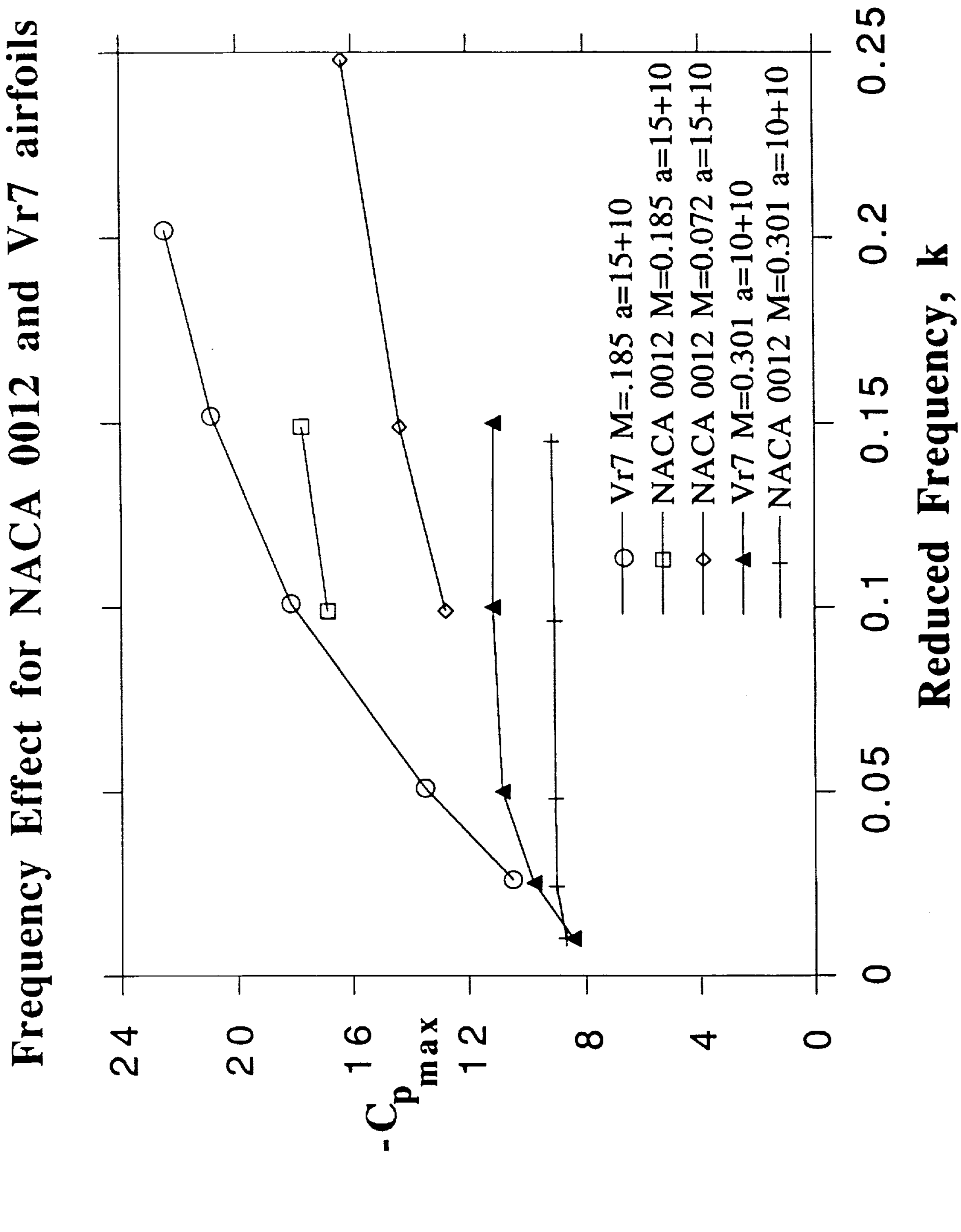
Maximum Suction Peak Limit
Vr7 Airfoil




Maximum Suction Peak Limit
Carta and Lorber data
$-C_{P_{max}}$
M_∞
k=0.0
Dynamic cases
Cp critical
0
2
4
6
8
10
12
14
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45

Mach Effect for NACA 0012 and Vr7 airfoils
k=constant




Frequency Effect for NACA 0012 and Vr7 airfoils
$-C_{p_{max}}$
0
4
8
12
16
20
24
0
0.05
0.1
0.15
0.2
0.25
Reduced Frequency, k
Vr7 M=.185 a=15+10
NACA 0012 M=0.185 a=15+10
NACA 0012 M=0.072 a=15+10
Vr7 M=0.301 a=10+10
NACA 0012 M=0.301 a=10+10

THE SUCTION PEAK ANALYSIS

- THE ONSET OF STALL IS THE CONDITION AT WHICH THE PEAK SUCTION ON THE AIRFOIL ATTAINS THE MAXIMUM VALUE BEFORE THE AIRFOIL REACHES THE MAXIMUM ANGLE OF ATTACK IN A COURSE OF UPWARD PITCHING MOTIONS PAST THE STATIC STALL ANGLE

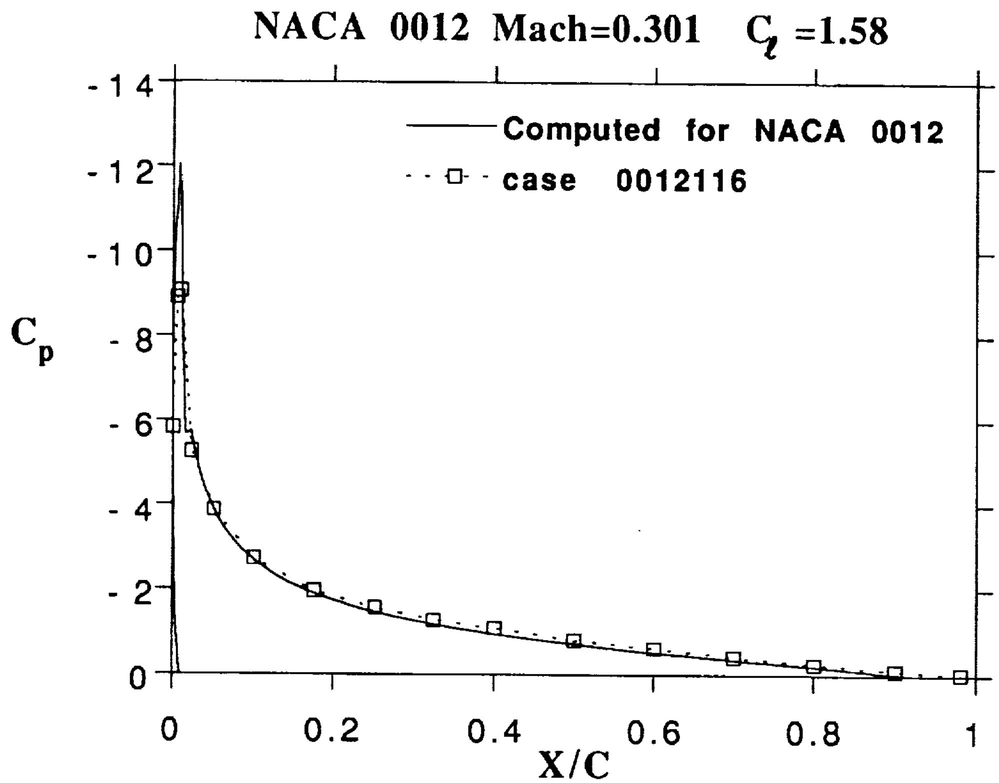
OBSERVATIONS

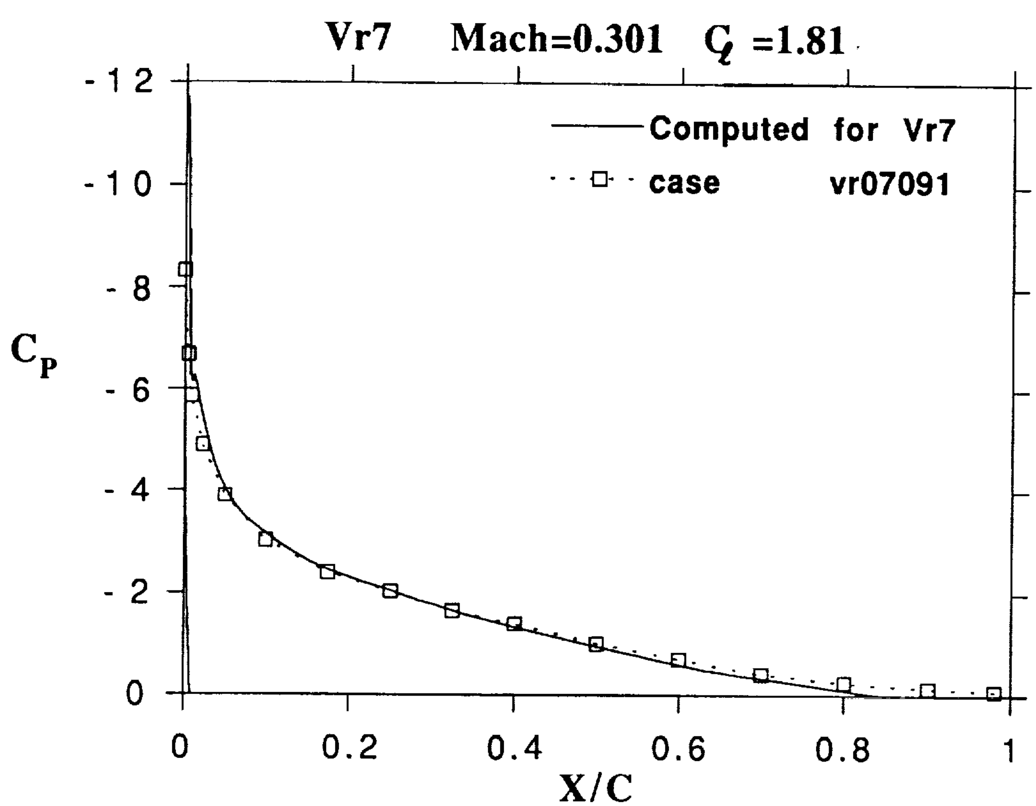
- MAXIMUM SUCTION PEAK INCREASES WITH k FOR MACH-SUBCRITICAL FLOW
- DECREASES WITH MACH NUMBER FOR MACH-SUPERCRITICAL FLOW
- QUASI-STEADY FLOW BEFORE STALL ONSET

WHAT ARE THE SEPARATION MECHANISMS?

- SHOCK INDUCED SEPARATION
- SEPARATION BUBBLE BURSTING
- TURBULENT SEPARATION

Experimental and Computed Pressures





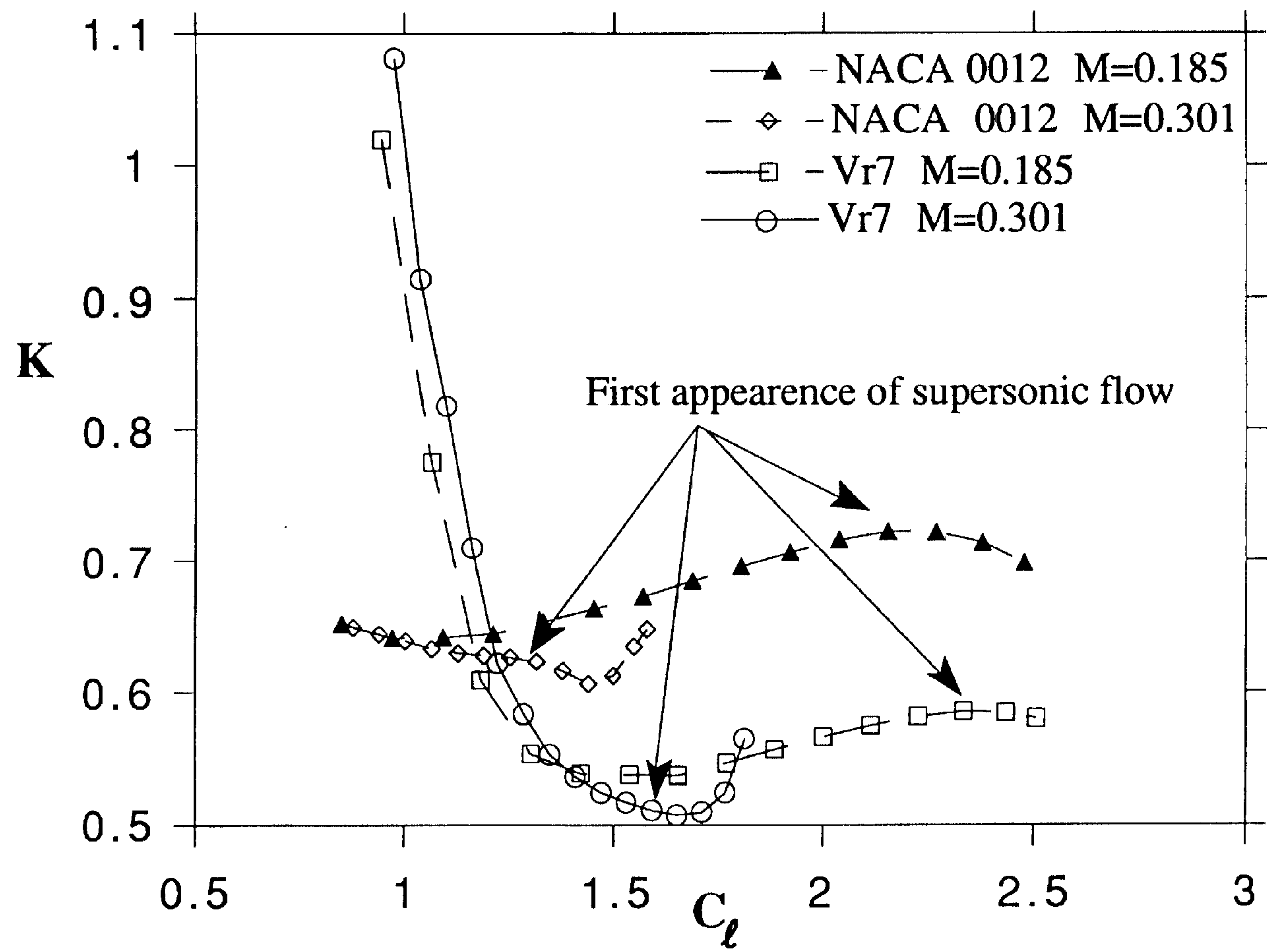
MOMENTUM THICKNESS AT SEPARATION

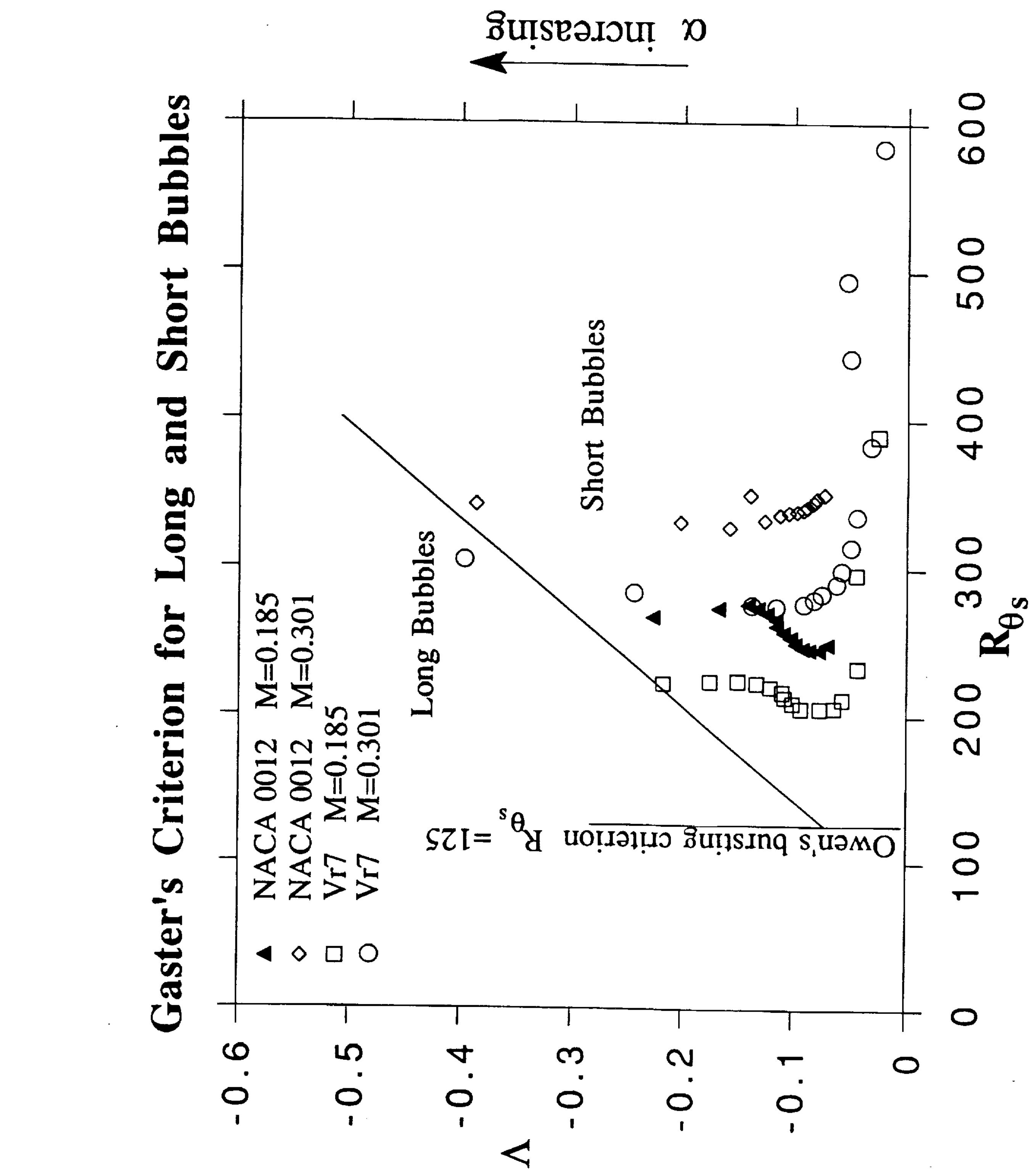
$$\delta_{S'} = 3.7\sqrt{\frac{0.441}{R}\left(\frac{U}{U_\infty}\right)^{-6}\int_0^{S'}\left(\frac{U}{U_\infty}\right)^{5} d\left(\frac{S'}{c}\right)}$$

CURLE AND SKAN'S BURSTING PARAMETER **K**

$$K = \frac{R_{\delta_{S'}}}{\sqrt{R}} \qquad R_{\delta_{S'}} = \frac{U_{S'}\delta_{S'}}{\upsilon}$$

Curle and Skan's Bubble Bursting Criterion




Gaster's Criterion for Long and Short Bubbles
NACA 0012 M=0.185
NACA 0012 M=0.301
Vr7 M=0.185
Vr7 M=0.301
Long Bubbles
Short Bubbles
Owen's bursting criterion R_{θ_s} =125
α increasing
Λ
R_{θ_s}
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0
100
200
300
400
500
600

CONCLUSIONS

- The maximum suction peak is limited by shock formation
- The shape of the leading edge determines the effect of unsteadiness on stall onset
- Before onset of stall the flow can be predicted by quasi-steady theory
- Transition point placement is not sensitive when the angle of attack is below the static stall value
- Transition point placement in supercritical flows is sensitive to movements of only one grid line